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The exposure of disadvantaged populations in freeway air-pollution sheds: a case study of the Seattle and Portland regions

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Abstract. Freeway-related air pollution and its harmful health risks have been observed in recent research in the environmental-health sciences. In this study we investigate the impact of freeway and arterial-road air pollution on vulnerable populations—for example, the poor, minorities, children, and the elderly—whose housing options are limited. Because many mobile-source emissions decay rapidly with distance, approaching background concentrations at 330 ft from the freeway, populations living near limited access roads are most at risk from exposure. Furthermore, microscale air monitoring systems are rarely in place at these locations in the United States. In this research we will define freeway air-pollution sheds with the aid of a geographic information system analysis and determine populations that may be at risk from exposure to mobile-source pollutants in two West Coast metropolitan areas (Seattle and Portland). We then use cluster analysis to identify key neighborhoods at risk in Seattle. Subsequently, we apply a hedonic pricing model to understand the extent to which house price values in Seattle are related to freeway proximity. Finally, we discuss policy options, planning implications, and mitigation measures, including an assessment of air-quality monitoring needs and land-use prescriptions.

1 Introduction

Traditionally, environmental-justice studies have focused on the disparate impact of air pollution on low-income and/or minority populations residing near stationary or point sources from industrial facilities or locally undesirable land uses.[1] However, if roadways are viewed as pollution line sources then an examination of populations living near high traffic densities that release both criteria as well as hazardous air pollutants, also known as 'air toxics') may also have environmental-justice implications. Six criteria pollutants are listed under the National Ambient Air Quality Standards required by the

[1] A recent example is the results of a lawsuit filed by the Air Quality Management District (AQMD) in Southern California against the oil company BP/Arco in March 2005. The lawsuit sought \$319 million because of violations at the company's Carson refinery between 1994 and 2002, the claim being based on the maximum penalty for each of thousands of violations. Within a week, BP/Arco settled for a total of \$81 million (\$6 million in past fees, \$25 million in cash penalties, \$30 million in community programs for asthma diagnosis and treatment, and \$20 million in emissions-reduction measures). This was by far the largest settlement ever negotiated by the AQMD, the country's largest and most effective air-pollution agency. Although the Carson refinery is a stationary source and not located next to a freeway, it is adjacent to a major arterial (Sepulveda Boulevard). Moreover, although Carson is one of the most racially integrated cities in the United States, most of the residents near the refinery are minorities. Thus, although this paper is focused on mobile sources, we do not want to give the impression that stationary-source pollution is not a problem. Indeed, when stationary polluting sources are located near freeways or arterials, nearby residents are in double jeopardy (Bacerra, 2005).

Table 1. Criteria pollutants—National Ambient Air Quality Standards. PM_{10} and $PM_{2.5}$ refer to particulate matter of less than 10 μm and 2.5 μm, respectively.

Clean Air Act—criteria pollutants	1 hour average	Annual arithmetic mean	8 hour average	24 hour average concentration
Carbon monoxide	35 ppm	na	9 ppm	na
PM_{10}	na	50 μg m^{-3}	na	150 μg m^{-3}
$PM_{2.5}$	na	15 μg m^{-3}	na	65 μg m^{-3}
Ozone	0.12 ppm	na	0.08 ppm	na
Sulfur dioxide	na	0.03 ppm	na	0.14 ppm
Nitrogen dioxide	na	0.053 ppm	na	na
Lead	na	na	na	1.5 μg m^{-3}

Notes: ppm—parts per million; μg m^{-3}—microgram per cubic meter; na—not applicable.

Clean Air Acts (see table 1). Emissions from the transportation sector (in 2002, the latest year for which data are available) accounted for 77.3% of carbon monoxide (CO); 54.3% of nitrogen oxides (NO_x); 44.8% of volatile organic compounds (VOCs), 12% of lead (Pb) releases, 6.4% of particulate matter of less than 2.5 μm ($PM_{2.5}$). 2.3% of particulate matter of less than 10 μm (PM_{10}), and 4.5% of sulfur oxide emissions (SO_2) (US Environmental Protection Agency, 2005). In addition, there are hundreds of elements and compounds emitted from the on-road and off-road vehicles. With support of recent findings from environmental-health sciences and epidemiology, the US Environmental Protection Agency recently identified a list of twenty-one mobile source air toxics. This listing is "to capture the collection of emissions potentially responsible for the cancer and noncancer health effects related to diesel exhaust" (US Environmental Protection Agency, 2001, page 8). Although the six *criteria* pollution levels have been reduced under the Clean Air Acts since the 1970s (Bae, 2004), researchers are finding more health risks related to, especially combustion-related, air toxics and ultrafine particles. For example, the Puget Sound Clean Air Agency reports that diesel soot is responsible for 70 – 80% of air-toxic-related cancer risks. The average air-toxic-related cancer risks are estimated to be in the 400 – 700 per million range in the Seattle region (Puget Sound Clean Air Agency, 2003, pages ES-4, ES-5).

Moreover, traffic is also a source of noise and vibration with the greatest impact on those living within 500 ft of major roads (US Department of Transportation, 1997). Although criteria pollutants and urban air toxics may also have microscale impacts, unlike noise, which is commonly measured and mitigated, mobile-source microscale 'hot spots'—for example, the roadside, freeways, rail roads, and bus depots—are rarely monitored in the United States because the Clean Air Act only requires ambient air-quality monitoring. These new findings are rarely reflected in local land-use planning decisionmaking processes (California Environmental Protection Agency and California Air Resource Board, 2005). As the urban-planning profession pays more attention to efforts to reduce urban sprawl via compact-city policies (for example, urban growth boundaries, smart growth), there is the threat of human-health costs to those living near freeways. In this paper we investigate land-use and population patterns near major roads in the Seattle and Portland metropolitan areas. Low-income and minority populations may be more at risk of exposure to mobile-source pollutants because of the search for affordable housing and because of land-use and transportation planning practices.

Although the amount of pollution released from mobile sources such as trucks and automobiles is dependent on such factors as traffic volume, fleet composition, fuel type, control technology, and vehicle speed, the potential for population exposure to these pollutants is also dependent on area topography, meteorological conditions, and

Table 2. Adverse health effects of mobile-source pollutants [modified from table 4.3 of Bates and Caton (2002)].

Pollutant	Definitive effect	Probable effect
Fine particles	aggravation of asthma (English et al, 1999) depressed lung function in school children (Wjst et al, 1993) increased risk of lung cancer increased prevalence of bronchitis	aggravation of acute respiratory symptoms (van Vliet et al, 1997) increased risk of wheezy bronchitis in infants (Gehring et al, 2002) decreased rate of lung growth in children
Ozone	increased hospital admissions for acute respiratory diseases aggravation of asthma increased bronchial responsiveness reduced lung function increased school absences for respiratory illness	effect on mortality
Diesel/VOCs [a] (in addition to particle effects)	increased response to allergens (Janssen et al, 2003) increased airway inflammation	increased risk of lung cancer increased risk of childhood leukemia (Crosignani et al, 2004)
Nitrogen dioxide	increased respiratory morbidity (Nitta et al, 1993) aggravation of asthma in children (Delfino et al, 2003) reduced rate of lung growth	
Carbon monoxide	increased cardiac ischaemia	increased hospital cardiac admissions

[a] VOCs—volatile organic compounds.

pollutant dispersion patterns, in addition to demographic and human-activity factors. Despite the complexity of these variables, there is a growing body of environmental-health and epidemiological evidence that populations living near limited-access freeways or high-traffic-density arterials may be at increased risk of exposure to mobile-source pollutants, which result in adverse health effects, such a lung cancer, leukemia, and asthma (see table 2 for details).[(2)]

2 Literature review

Proximity to high traffic densities can be considered a surrogate for individual exposure, although researchers have used a variety of methodologies to measure proximity and traffic volume and/or densities. Huang and Batterman (2000) examined forty-five epidemiological studies that used residential location as a measure of environmental exposure, with distance from the pollution source to the receptor (school, residence) as the most common methodology for determining exposure. Several studies have used circular buffer zones around the receptor, assuming equal pollution dispersion, and others have used a combination of receptor zones and proximity to major roads.

A Tokyo study determined that, on the basis of the dispersion gradient of NO_x, traffic emissions could have adverse health effects on populations residing within 150 m of major roadways (Nitta et al, 1993). The validity of distance from major roadways as a measure of exposure to air pollution from traffic was investigated by a Dutch team

[(2)] Workers at sites close to freeways and major roads are also at risk, but these are not specifically included in our study.

who measured outdoor levels of PM_{10}, $PM_{2.5}$, black smoke, benzene, and NO_2 at different distances from the roadway (Roorda-Knape et al, 1998). This study concluded that traffic intensity, distance, and wind direction are all important variables when considering population exposure to mobile-source pollutants. Wind direction was also important in an Australian study (Hitchins et al, 2000).

Another methodology adopted by researchers investigating an association of childhood asthma with proximity to roadway pollution was based on determining traffic density within residential buffer zones (Lin et al, 2002). In this study, traffic density was calculated by multiplying the length of road segment within the buffer by the annual average daily traffic count of the specific roadway. Traffic density was then categorized into low, medium, or high, with the latter specified as $\geqslant 4043$ vehicle miles traveled (VMT) in a 200 m buffer or $\geqslant 18\,765$ VMT in a 500 m buffer. The study concluded that there was a correlation between high volumes of traffic or a high percentage of trucks within a 200 m residential buffer for children hospitalized with asthmatic episodes. Zhu et al monitored ultrafine particles (that is, less than 0.1 μm in diameter) at various distances from a nine-lane freeway in Southern California in order to determine the dispersion gradient of these particles (see figure 2 of http://www.ph.ucla.edu/magazine/PHmgnov02research.pdf and Zhu et al, 2002 for details). The researchers concluded that people who live, work, or travel within 100 m downwind of major traffic sources may have a much higher ultrafine-particle exposure than those who live further from such sources.

Of particular interest in epidemiological research is the effect of mobile-source pollutants on sensitive populations such as children. Wjst et al (1993) reported that with each increase of 25 000 cars on a main road near schools the lung function of children decreased by 0.71%. This work was soon followed by various research initiatives, especially led by Brunekreef and his colleagues in the Netherlands. Their findings indicated that children living or attending schools within 100 m (330 ft) of truck traffic had poorer lung function, leaving the researchers to hypothesize that this may be the result of long-term exposure to ultrafine particles (Brunekreef et al, 1997). The Brunekreef research team also conducted a detailed study of respiratory symptoms. After accounting for confounding factors of socioeconomic status and related lifestyle considerations (for example, smoking in the home, unvented gas-fired heaters) their results suggested that an association between traffic-related air pollution and respiratory health was mainly restricted to the children of intermediate and low socioeconomic status (van Vliet, 1997). Such findings imply that a demographic analysis of populations living near major arterials could reveal that minority or low-income populations are disproportionately impacted by mobile pollution sources.

Several US-based studies were also concerned with the environmental-justice implications of exposure to mobile-source pollutants; that is, are low-income or minority populations more at risk? (Delfino et al 2003; English et al, 1999; Forkenbrock and Schweitzer, 1999; Green et al, 2004; Gunier et al, 2003; Kinney et al, 2000; Korenstein and Piazza, 2002; Lena et al, 2002; Loh and Sugerman-Brozan, 2002; Samet et al, 2001; Wilhelm and Ritz, 2003.) The Forkenbrock and Schweitzer study adopted a similar procedure to the one used in this research, a geographic information systems (GIS) approach at the census-block level, and developed a pollutant-dispersion model to measure the impact of highway projects on low-income and/or minority populations in the City of Waterloo, Iowa. However, their research is more of a demonstration of an air-pollution and noise-pollution modeling methodology to a very small microlocation than a metropolitan-level analysis. A more traditional epidemiological approach was conducted by English et al (1999), also using GIS, to determine whether living near busy roads may be associated with asthma among children of low-income populations

in San Diego County, California. This study concluded, on the basis of traffic counts within a 550 ft (~165 m) buffer of children's homes, that living near high-volume traffic was a contributing rather than a causal factor in asthma development. The buffer size was selected on the basis of an examination of several air-emission dispersion models that indicated a 80–90% decay of pollutants between 492 ft and 656 ft. It is also important to note that the earlier Dutch study by Roorda-Knape et al (1998) suggests that traffic pollutants in or near schools are a more relevant measure of exposure because children spend most of the daytime at school during periods of high traffic flow.

The California-based research of Korenstein and Piazza (2002), Green et al (2004), and Gunier et al (2003) further investigated the proximity of schools to major roads. Korenstein's team developed dispersion-modeling estimates of PM_{10} concentrations at four predominantly Hispanic urban schools, three of which were 150 m (~500 ft) from major roads with up to 250 000 vehicles per day (VPD). Although the results indicated that predictive concentrations were much lower than regulatory levels (either federal or California standards), the authors stated that below-regulation concentrations have still been shown to cause significant negative health effects.

Green et al (2004) studied the demographics of California schools (173 schools with more than 105 000 students) located within a 150 m (~500 ft) high traffic buffer and found that, as the traffic-exposure category increased, then the percentages of Hispanic and of non-Hispanic black children attending schools in those categories increased and the percentage of non-Hispanic white children decreased. The study also found that poverty was related to traffic exposure, which supports the earlier findings of Gunier et al, in which the researchers concluded that Hispanic, African-American, and Asian children in the lowest income quartile were on average three to five times more likely than children in the highest income quartile to live in block groups with high traffic densities (Gunier et al, 2003). Community-based studies of the Bronx, New York (Kinney et al, 2000), and of Roxbury, Massachusetts (Loh and Sugerman-Brozan, 2002), found similar results. A survey of 1109 parents in East Bay, San Francisco, that inquired about their children, found a strong association between asthma symptoms and NO_x and PM levels (Kim et al, 2004).

Currently in the United States there are few policy initiatives beyond the regulatory requirements of the Clean Air Act to address the adverse health impacts from exposure to mobile sources. In California, Senate Bill 352 prohibits the siting of new schools within 500 ft of a busy road, defined as traffic in excess of 50 000 VPD in a rural area and 100 000 VPD in an urban area (California Department of Education, 2004).

Two recent court cases also had the potential to influence public policy. The first involved a lawsuit filed by the Sierra Club and other litigants regarding the need for a supplemental environmental impact statement to address the potential impacts of a highway expansion in Las Vegas, Nevada, on the health of nearby residents. Considered a potentially precedent-setting case, the US District Court for the District of Nevada recently found that the Federal Highway Administration met its requirements in issuing an environmental-impact statement and denied all seven counts of the Sierra Club's summary judgment motion [*Sierra Club v Mineta* D.Nev., (No. CV-S-02-0578-PMP-RJJ)]. In 2002 several environmental and labor groups filed suit against the US Department of Transportation with respect to the need for considering the localized adverse impacts of Mexican truck traffic. In 2003 the US 9th Circuit Court of Appeals ruled that the National Environmental Protection Act required the US Department of Transportation "to consider the most likely localities to be affected by increased truck traffic and to perform more localized analyses for these areas" and that simply placing the potential pollution increases in the context of US national emissions was inadequate [*Public Citizen v Dept of Transportation* (No. 02-70986 9d Cir. 2003)]. This ruling

suggests that regional air-quality monitoring does not provide adequate data sources for microscale environments, such as populations living near major roads.

3 Data and GIS analysis

In our research we examine land-use patterns near major roads to determine the number of residences impacted and to identify the populations at risk of exposure to mobile-source air pollution. We also examine the demographics of populations that live near limited-access freeways in the Seattle and Portland metropolitan areas, in order to determine if low-income, minority populations are at increased risk of exposure to mobile sources. In addition, we investigate the prevalence of schools and senior facilities located within the areas that we describe as a *freeway air-pollution shed* (FAPS), specifically a 100 m (330 ft) buffer from roadways with a minimum of 100 000 VPD, a definition that encapsulates the results of the research investigations. The 330 ft buffer is supported by several research studies, both in the United States and in other countries (especially Zhu et al, 2002 and Brunekreef et al, 1997), although, as pointed out above, California's statutory limit (as an example) is 500 ft. The rationale for the buffer of this extent is the distance decay rate for ultrafine particles from freeways (and arterial roads). Our study is an attempt to bridge the inderdisciplinary knowledge required for land-use, transportation, and air-quality planning to identify whether there is a disproportionate impact on minority and low-income populations.

Our study areas include the urban-growth boundary regions of Seattle, WA, and Portland, OR. In Washington State this area was defined as approximately 310 000 acres of western King County. The Portland study area was defined by the three Oregon Counties of Clackamas, Washington, and Multnomah, totaling approximately 232 000 acres.

From the Census 2000 Summary File 3, we compiled demographic, social, economic, and housing data at the census-block group level, the smallest geographic unit for the required socioeconomic data, for these areas. Parcel data were combined with tax-assessor records to develop a database of single and multifamily residences. The multifamily-residence data include the number of dwelling units in each building, which was used to assess the number of housing units in each block group.

An exhaustive list of schools (K – 12) was collected from both King County and the Portland metropolitan area. The locational information was combined with specific data from each respective State's Department of Education database to show enrollment, demographics, and the number of students on free or reduced lunch programs.

We obtained average annual daily traffic (AADT) volume data for 2000 for all limited-access arterials in western King, Clackamas, Multnomah, and Washington counties. High-traffic roads were identified as having more than 100 000 vehicles per day. Specifically, these were Interstates 5, 405, and 90; state road 520 in western King County; and Interstates 5, 84, 205, and 405 in the Portland urban growth area (UGA).

Schools, parcels, census-black groups, and traffic files were compiled within a GIS (ArcView). Parallel lines were then created within 400 ft of the selected road network. This buffer accounted for both the 330 ft conservative dispersion estimate of mobile-source pollutants as well as an additional area of the roadway (ArcView measures distance from the middle of the roadways and not their edge). These areas, designated as FAPS, were analyzed for socioeconomic demographics, single versus multifamily residences, and schools.

Although the census-block group is larger than the FAPS, we had little alternative than to ascribe to socioeconomic characteristics of the block group population to its FAPS subset. A proportion was created by calculating the number of residential units

in the FAPS and those in the block group, and by using this as a ratio to estimate the demographic characteristics of the FAPS.

4 Descriptive results

An interesting comparison emerges when we look at the Seattle and Portland FAPS. Although the Portland UGA is smaller than the King County's UGA discussed in this paper, in terms both of population and of area, it is slightly denser (5.7 and 4.8 persons per acre, respectively). Despite the higher density, the proportion of persons living within Portland's FAPS is considerably smaller than that living in King County's, 0.42% versus 1.81%. A striking finding is that single-family home development since 1990 was *five* times higher than in the 1980s in the Seattle FAPS. In both areas, poor and/or African-American residents are represented in disproportionately higher numbers in the FAPS. The number of poor living in the Seattle and Portland FAPS is more than 1.21 and 1.36 times higher, respectively, than that in the UGAs at large, and the concentration of African-Americans is higher than that of other minority groups (Asian-Americans and Hispanics), and 2 – 3 times higher than that of the general UGA population. In summary, there is a strong tendency for low-income and/or nonwhite populations to live in FAPS (see tables 3 and 4).

Although the concentration of children in the core areas of Seattle and Portland is not particularly high, it is worthwhile to look at the number of schools and students in both FAPS. This illuminates the potential harm to young populations. Of the sixteen educational facilities within the Portland and Seattle FAPS, there are ten elementary schools, two middle schools, three high schools and an administration building. Total student enrollment is more than 6600. All these schools have a high proportion of minority students and students from low-income household (as reflected in the receipt of free or subsidized meal programs), except for the two private schools in suburban Bellevue.[3] Seven of the FAPS schools have a nonwhite majority (between 52% and 95%), and more than 50% of students in five schools received free or subsidized meals.

5 Cluster analysis

Focusing on Seattle as our first and local study area, we applied a cluster analysis to assign all the 2000 Census-block groups in the Puget Sound region (2750 of them) to see whether there is a spatial residential association with income level and race. Though each block group has its own characteristics, it is useful to classify the census-block groups into several clusters that have similar characteristics; these may or may not be spatially contiguous.

Cluster analysis partitions data into meaningful subgroups. It is particularly useful when the number of subgroups and other composite information are unknown a priori (Fraley and Raftery, 1998). The result of cluster analysis is a number of heterogeneous groups with a more or less homogenous content. A major task is identifying the optimum number of clusters. There is no generally accepted theory, so decisions are based on subjective interpretation. Fraley and Raftery (1998; 1999; 2002) developed a model-based clustering analysis technique using an expectation maximization (EM) algorithm. Traditional cluster analysis often has problems in determining the structure of clustered data. However, the EM approach significantly alleviates these problems.

[3] Whereas FAPS schools in low-income communities tend to have minimal or no buffers next to the freeway, these two private schools are surrounded by dense trees. This hints that there may be some awareness among educators and parents in wealthy communities about the problems associated with proximity to freeways. On the other hand, it could be a signal of less-than-perfect information even among the wealthy and highly educated, because trees are a much better noise buffer than a pollution filter.

Table 3. Socioeconomic characteristics of Seattle's urban growth area (UGA) and freeway air-pollution sheds (FAPS). Source: US Census of Population (2000).

Variables	UGA	Percentage	FAPS	Percentage	Percentage of UGA	FAPS/UGA share ratio
Area (acres)	310 380		17 073		5.50	
Population	1 491 633	100	26 977	100	1.81	
White	1 060 551	71.10	17 813	66.03	1.68	0.93
Black	87 241	5.85	2 947	10.92	3.38	1.87
Hispanic	86 956	5.83	1 483	5.50	1.71	0.94
Asian	176 363	11.82	3 462	12.83	1.96	1.09
Children	283 847	19.03	3 864	14.32	1.36	0.75
Seniors	165 144	11.07	2 789	10.34	1.69	0.93
Income below poverty	132 950	8.91	2 912	10.79	2.19	1.21
Schools [a]	427		8		1.87	

[a] Source: Washington State Department of Education.

Table 4. Socioeconomic characteristics of Portland's urban growth boundary (UGB) and freeway air-pollution sheds (FAPS). Source: US Census of Population (2000).

Variables	UGB	Percentage	FAPS	Percentage	Percentage of UGB	FAPS/UGB share ratio
Area (acres)	232 380		6 415		2.76	
Population	1 328 195	100	5 633	100	0.42	
White	1 047 027	79	3 891	69	0.37	0.88
Black	40 996	3	532	9	1.30	3.06
Hispanic	110 492	8	469	8	0.42	1.00
Asian	74 452	6	389	7	0.52	1.23
Children	289 096	22	1 076	19	0.37	0.88
Seniors	138 519	10	630	11	0.45	1.07
Income below poverty	128 319	10	741	13	0.58	1.36
Schools [a]	366		8		2.19	

[a] Source: Oregon State Department of Education (2004).

It assumes that the data are generated by a mix of underlying probability distributions in which each component represents a different cluster or group. The EM clustering algorithm computes probabilities of cluster memberships on the basis of one or more probability distributions instead of assigning cases or observations to clusters to maximize the differences. The clustering algorithm then chooses the number of clusters that maximize the overall probability or likelihood of the data using the Bayesian information criterion.

In our study, this approach yielded seven clusters based on income and race. As suggested by the data in table 5, clusters 1 and 2 are significantly different from the others, especially in terms of racial mix and income. Cluster 1 is characterized by the only minority-group majority share (75%) and highest percentage of children and the elderly (33%). The general location of this cluster is south of downtown Seattle and west of Lake Washington and the Port of Tacoma. The next cluster (cluster 2) has a much lower income ($34 634) level than that of clusters 3 – 7 (which range approximately from $50 000 to $90 000) although its white-population share is not much lower than that of cluster 3. Another group near the freeway is characterized by high income

Table 5. Cluster analysis of 2000 Census-block groups, Central Puget Sound, WA. Source: US Census of Population (2000).

Cluster	Percentage white population	Median household income ($)	Median housing value ($)	Percentage children and the elderly of total population [a]
1	35	38 696	161 445	33
2	69	34 634	151 566	28
3	88	53 012	155 957	31
4	73	57 986	191 837	30
5	93	64 458	241 644	30
6	87	71 355	339 953	27
7	81	93 342	563 392	32

[a] Children defined as being less than 18 years of age, the elderly defined as those over 65 years of age.

and is white dominant (cluster 6). The contrast with clusters 1 and 2 is striking, but the explanation is proximity to Lake Washington and mountain views, Microsoft, and somewhat lower traffic volumes. Figure 1 shows the spatial distribution of clusters in the Puget Sound region, and confirms our a priori expectation of low-income and minority households living close to freeways (especially the Interstate 5 corridor) and major arterials.

6 Hedonic price analysis

If there is residential market segmentation, how do residents value living near freeways? Do residents capitalize the negative externalities into lower house prices? To test this, we undertook a hedonic price analysis of house-price sales data (in 2000) in King County, WA, the core county of the Seattle metropolitan region. King County property sales records, parcel data, census-block-group-level information, and regional travel and employment data from the Puget Sound Regional Council (the regional Metropolitan Planning Organization) were used. Only single-family houses were included in the analysis.

Housing sales transactions may not occur at random among the stock of housing units. Housing units that were sold in year 2000 may differ in measured and unmeasured characteristics from the houses not sold. However, we analyzed only the houses sold. Therefore, there is a potential selection bias problem. The unmeasured characteristics may lead to biased estimates of the parameters; to avoid this, we used a popular selection bias detection and correction method [the Heckman two-step estimation procedure (Heckman, 1979)].

The Heckman procedure consists of two stages. In the first stage a probit model is estimated to predict the houses sold in year 2000 with the data that contain all houses in the study area. The residuals of the probit model reveal information about the unmeasured characteristics that distinguish sold housing from unsold housing. The inverse Mill's ratio of selection-bias control factor called lambda is calculated in the process through the use of normally distributed residuals. In the second stage a regression analysis is performed with the selection-bias control factor lambda as an additional covariate. This factor reflects the effect of all the unmeasured characteristics related to the sales transaction choice, and the coefficient captures the partial effect of these unmeasured characteristics. The process produces unbiased estimates for the covariates in the hedonic pricing model. Additional steps to correct the standard errors



Figure 1. The spatial distribution of residential clusters in Central Puget Sound, WA.

were also performed (for detailed information for the application of the Heckman procedure, see Smits, 2003).

Also, in the hedonic pricing model spatial autocorrelation is an important issue because it results in biased parameter estimates. We included census-block-group-level neighborhood information to capture the effects of neighborhood. However, spatial autocorrelation is largely attributed to omitted variables, and a degree of spatial autocorrelation may be unavoidable. Using CrimeStat, a spatial-analysis software program, we conducted a spatial-autocorrelation test. The results show that the Moran's

I value and *z*-statistic value of normality for the residuals of the predicted dependent variable (log of sales price) were 0.0067 and 21.24, respectively. The Moran's *I* value indicates that there is positive and statistically significant spatial autocorrelation. However, the Moran's *I* value and *z*-statistic value for the observed dependent variable were 0.1253 and 383.02, respectively, suggesting a significant reduction in spatial autocorrelation.

In table 6 the results of the hedonic regression model are adjusted for selection bias and the correction of standard errors. A significant negative parameter estimate of lambda implies that the houses sold in 2000 compared with the houses not sold have unmeasured characteristics negatively related to sales price.

The dependent variable, housing sales price, was log-transformed because the price does not have negative values and is not bounded, and its distribution is skewed to the left. Only the statistically significant independent variables at the 0.05 level were retained in the model. Table 6 also includes a variance inflation factor (VIF) to examine multicollinearity among the independent variables. The VIF values indicate that the independent variables in the models are not collinear.

Table 6. Results of the hedonic pricing model for King County, Seattle metropolitan area. Source: King County Department of Assessment (2000).

	Coefficient	SE [a]	$Pr > \|t\|$	VIF [b]	Elasticity
Intercept	11.2008	0.5234	<0.0001	–	–
Housing characteristics					
Lot size ($\times 1000\,ft^2$)	0.0017	0.0001	<0.0001	1.1165	0.17
Total living area ($\times 1000\,ft^2$)	0.1660	0.0090	<0.0001	3.1739	16.62
Year built	0.0006	0.0002	0.0070	2.9734	0.06
Construction quality	0.1260	0.0063	<0.0001	3.7865	12.52
Housing renovated	0.1177	0.0257	<0.0001	1.1330	11.05
Housing condition good	0.0498	0.0112	<0.0001	1.3385	4.51
Housing condition very good	0.1512	0.0213	<0.0001	1.2321	15.09
Parcel characteristics					
View	0.0677	0.0205	0.0010	1.2632	5.91
Waterfront	0.2868	0.0428	<0.0001	1.7782	30.40
Tideland/shoreland	0.3330	0.0663	<0.0001	1.7496	34.97
Traffic noise moderate	−0.0399	0.0186	0.0326	1.0540	−4.80
Traffic noise high	−0.0457	0.0159	0.0042	1.1557	−5.22
Other nuisances	−0.0804	0.0243	0.0010	1.0733	−8.84
Stream	0.1818	0.0414	<0.0001	1.0911	17.48
Within FAPS [c]	−0.0780	0.0155	<0.0001	1.1912	−8.21
Neighborhood (census-block group) characteristics					
Population density ($\times 100\,000\,ft^2$)	0.0026	0.0004	<0.0001	1.7844	0.26
Median housing value (×$1000)	0.0013	0.0000	<0.0001	2.1403	0.13
Average household size	−0.1044	0.0136	<0.0001	2.6643	−10.56
Percent homeowners	0.0026	0.0003	<0.0001	2.8850	0.26
Percent commuting by automobile	−0.0038	0.0007	<0.0001	2.3376	−0.38
Percent black population	−0.0053	0.0009	<0.0001	1.4874	−0.53
Retail service accessibility	0.0823	0.0077	<0.0001	2.6194	8.23
Lambda	−0.8205	0.0841	<0.0001	2.6194	–

Adjusted $R^2 = 0.7271$
$n = 5237$

[a] Standard error.
[b] Variance inflation factor.
[c] Freeway air-pollution shed.

The elasticity coefficient shows the proportional change in the dependent variable associated with a proportional change in independent variable. However, in this case we calculated the proportional change in sales price for a one unit change in the independent variable in order to permit an easy interpretation of the effects of explanatory variables on the response variable. For instance, a 1000 ft^2 increase in total living space results in a 16.62% change in the predicted sales price of single-family housing, holding all other things constant. The elasticities of the binary variables were also calculated. The elasticity of a dummy independent variable indicates the proportional change in the dependent variable associated with a binary change in the independent variable. For example, the key to this analysis, the sales price of single-family housing inside FAPS is, ceteris paribus, 8.21%, $100\{\exp[\beta - (\mathrm{var}\,\beta/2)] - 1\}$, lower than housing outside FAPS. This is larger than the characteristic most closely associated with locations near freeways—that is, traffic noise (4.8 – 5.2% comparing moderate to high noise levels). The inference is that, even with imperfect information, pollution is more important than noise.

7 Qualifications

There are three major qualifications to this research. First, our focus on the long-term health impacts of air pollution (especially PM) should be tempered by the increasing recognition that there may be health damages associated with even short-term exposure to air pollution. This has been noticed by several research studies in different locations with different air pollutants. Examples include the exposure of children to diesel-related pollutants during school-bus commutes in Los Angeles (Winer et al, 2005), the ozone exposure of schoolchildren, especially during school breaks (Peters et al, 1999), the exposure to fine PM of home dwellers (both indoor and outdoor) and workers in Helsinki (Jantunen et al, 2004), and the CO exposure of street sellers in Mexico City (Fernandez-Bremauntz et al, 1993).

The second qualification is related to the fact that there is no widespread roadside monitoring in the United States, as opposed to many European countries, so that our research is based on inferences drawn from ambient air-quality levels and from the small number of sample surveys that have been undertaken. Furthermore, the officially sponsored studies in the United Kingdom reveal ambiguous conclusions about whether PM emissions close to roads exceed even long-term standard objectives. For example, data for 1999 or 2000 in fifteen cities exceeded the 2004 standard at only five of the thirty-four sites, whereas in London the standard was exceeded at only two (Camden and Marylebone Road) out of eight sites (Air Quality Consultants Ltd, 2002). Nevertheless, in a more recent official study (DEFRA, 2005), kerbside levels of nanoparticle emissions were much higher at the Marylebone Road site than background levels at other sites, both in London and elsewhere. In another study, in Winchester town centre, emissions failed to achieve the 24-hour mean standard of 50 $\mu g\,m^{-3}$ (as measured by thirty-five failures per year or more) in five years 1997 – 2004, and last passed in 2001 (City of Winchester, 2005). A major problem with the UK monitoring hitherto is that it mainly tests for PM_{10} emissions; for example, there are only three $PM_{2.5}$ monitoring sites in London compared with thirty-five PM_{10} sites (Air Quality Consultants Ltd, 2003). It is clear now that the dangers from roadside PM are much more serious for $PM_{2.5}$ and ultrafine particles.

A third and obvious qualification is that 90% of PM emissions are not transport related, so that a comprehensive assessment of their health impacts needs to look at other sources. This is a complex question, however, because there is not a one-to-one correspondence between emission sources and health impacts. For example, particulate emissions are particularly high in agricultural regions and desert areas, both of which are relatively sparsely populated.

8 Policy and planning implications

As we have reported, there is an increasing mound of evidence that freeways, major arterials, and other traffic density zones inflict significant health damage on those who live and work nearby. Also, recent research shows that the most dangerous pollutants are ultrafine particles and diesel-related VOCs, whereas the jury is still out on the long-term health impacts of ground-level ozone, in part because of the possibility that, within certain ranges, NO_x may have protective effects against ground level ozone exposure. A problem is that scientists disagree about the dollar value of these health costs, although all of them agree that these costs are very high. There is little effort to mitigate these freeway-related pollution impacts, although a start is being made in California (California Environmental Protection Agency and California Air Resource Board, 2005).

However, without the advantage of a relatively precise cost – benefit analysis, it is difficult to prescribe the most appropriate policy and planning responses. Because the scientific community is only now beginning to appreciate the extent of the dangers, it is unreasonable to expect that people living or working near freeways would have the same degree of information. They are probably well aware of the noise and somewhat aware of the higher pollution levels. In making their location decision, residents trade-off lower rents and house prices against these disadvantages, but with limited information. So, a 'first, do no harm' principle would be to give the information as it becomes available to residents to that they can decide (at lease end or some other stage) whether to move or stay.

Another issue is that the conclusions about air-pollution emissions near freeways are still largely based on infrequent surveys or inferences from other locations. A key priority is to set up roadside air-pollution monitors at regular intervals along freeway routes. This is not a zero-cost option, but the costs are relatively low compared with the benefits from increased knowledge that can empower the will to act.

Assuming that the knowledge of more damage will be built up over time, what else (if anything) should be done about it? One obvious option for planners is zoning remedies. These could range in scope from land-use restrictions on new housing (planners have allowed 4387 housing units to be built in the Seattle FAPS since 1990, one fifth of the housing built since 1900), schools, daycare centers, senior-citizen centers, and other facilities, to the compulsory relocation of existing land uses (with or without compensation). An intermediate position is to allow commercial and industrial facilities, although worker exposure is also a problem (even if mitigated by reduced hours of exposure relative to residents, lower employment densities than residential densities and up-to-date filtration systems in modern office buildings).

A different route is via the strengthening of the controls on the sources—that is, trucks, cars, and other vehicles. However, even assuming the political will exists, these policy changes would take a long time (more than twenty years) to implement. Limitations on new-truck diesel emissions do not begin until 2007, and the truck fleet is very durable (with an average lifetime of up to thirty years). Restrictions on truck routes, and perhaps even times of travel, may merit inquiry, but many metropolitan areas (including Seattle and Portland) have a too-limited highway infrastructure to permit much route diversion. There are some modest technical fixes: ultra-sulfur and high-performance diesel fuel and financial incentives to retrofit particle traps, and retrofitting to use alternative fuels. New automotive technologies (from hybrids to fuel cells) are beginning to show promise, but rates of adoption and fleet turnovers are very slow.

Yet another approach is via better health monitoring of and targetted healthcare for residents and workers within FAPS. This would help, but the sharply rising costs of healthcare are a major obstacle, given the evidence of the numbers with impaired health. Also, in any event, prevention is much better than a cure.

Pragmatically, we may have to be content with more modest strategies:
(1) more research and education on air quality (Stone, 2003), finding ways of making new knowledge accessible so that locators can make more informed decisions.
(2) roadside monitoring of emissions; and
(3) restrictions on new land uses within FAPS.

The latter point brings up an important concern. Infill of all vacant sites and the redevelopment of obsolete land uses at higher residential densities are very consistent with the densification objectives embedded in the Growth Management Acts of Washington and Oregon. However, many of these sites are close to freeways, and developing or redeveloping them exposes people to significant pollution-related health damage. Land-use planning and regulations are currently ill prepared to mitigate these impacts.

9 Conclusions

This research tested three related hypotheses: (1) minority and/or low-income households live disproportionately close to freeways compared with white and middle-income households; (2) households in each category cluster together in local subhousing markets; and (3) negative environmental externalities near freeways (especially air pollution) are capitalized in house prices and rents. First, the results support all three hypotheses and their corollaries: the clustering of low-income and minority population near freeways, and the higher concentration of minority and/or poor students in FAPS. Health consequences for these children can be more harmful, because of the effects of pollution on their lung development. Second, the cluster analysis suggests that the residential choices of the minority and/or low-income population are limited. Third, locations within a FAPS are negatively associated with housing prices when other negative environmental factors such as traffic noise are accounted for. Of course, for people living in such locations, trade-offs may have to be made: cheaper housing versus higher health risks.

Of course, there are some qualifications to our research. Our hedonic price analysis is based on house prices, whereas many residents within FAPS are renters. Also, ideally, we would like a finer grain of detail for our socioeconomic data than the census-block groups. The most significant point of all is that, though Zhu et al (2002) have provided us with a useful grounding for deriving the FAPS boundaries, their study was based on one metropolitan area and hence cannot take account of location-specific variations (although the boundaries appear to receive some support from earlier European studies).

At the practical level, in a perfect world we would need a series of air-pollution monitoring devices along each freeway in all metropolitan areas, given that this is a health issue of some importance. The United States could learn from the experiences of the United Kingdom and European Union with monitoring roadside air pollution. We also need a strategy to mitigate the costs of this problem (possibly, but not necessarily, to the extent of compulsory relocation of homes and workplaces within FAPS); whether this would justify relocation assistance is a question for policymakers. Only when problems of this kind are seriously addressed can we be assured that the parallel social problem of environmental justice is receiving the public policy attention that it demands and deserves.

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